



A Large Drift Detector Array Lunar Orbiter Spectrometer

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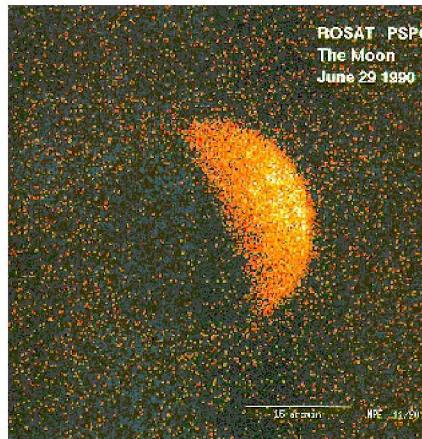
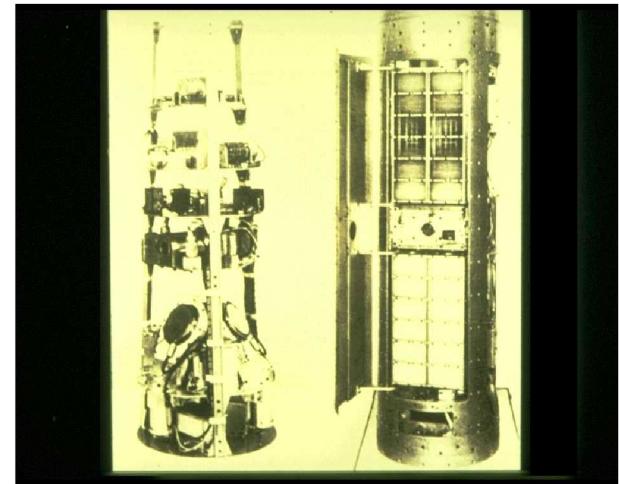


Background



Birth of X-Ray Astronomy

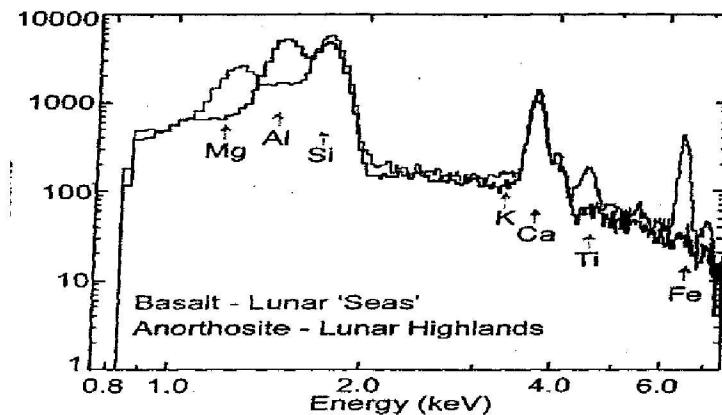
- In 1962, Riccardo Giacconi and colleagues at AS&E flew sounding rocket to look at x-ray fluorescence from the moon
- Lunar signal was overshadowed by very strong emission from the Scorpius region
- Discovered the first extra-solar x-ray source, Sco X-1, and pervasive x-ray background
- This was the effective birth of x-ray astronomy



The German-led ROSAT mission took the first x-ray image of the moon in 1990

Introduction

- Measurement of x-rays from the surface of objects can tell us about the chemical composition
 - Absorption of radiation causes characteristic fluorescence from material being irradiated.
 - By measuring the spectrum of the radiation and identifying lines in the spectrum, the emitting element (s) can be identified.



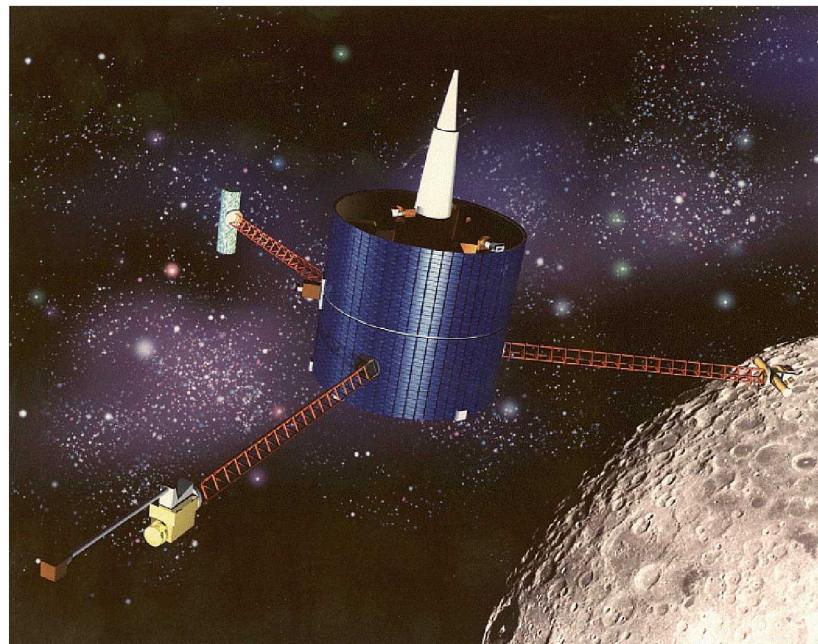
This technique works for any object that has no absorbing atmosphere and significant surface irradiation : Our Moon, the icy moons of Jupiter, the moons of Mars, the planet Mercury, Asteroids and Comets



Lunar Surface Analysis



- *On the lunar surface, the fluorescent x rays are produced by solar x-ray irradiation. For surface-element analysis, need an x-ray spectrometer in Lunar orbit.*
 - *Can use a simply collimated detector looking down at surface. As it scans the surface it records the spectrum in the field of view, as a function of time, to map out the elements*



Lunar Prospector

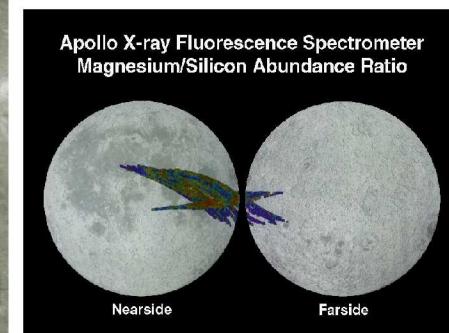
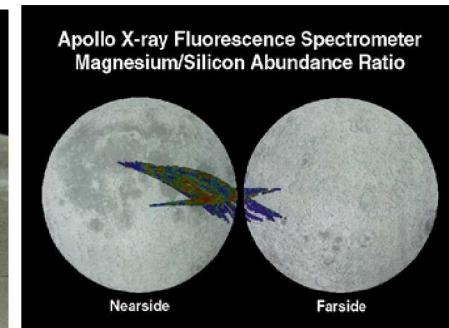
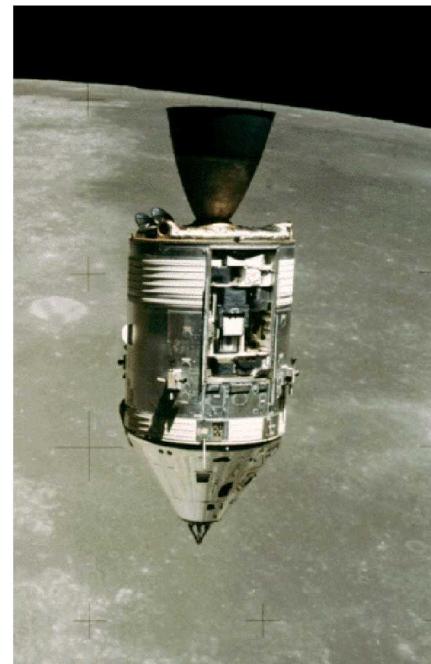


Past Missions



There are several missions (past and present) with the goal of mapping the lunar surface.

Apollo 15 & Apollo 16: XRS mapped Mg, Al, and Si at the lunar nearside equatorial regions - covered ~9% of the total lunar surface with a resolution of ~100km and energy resolution of ~800eV @ 6.4keV using large area proportional counters (1971).



Clementine Provided global estimates of FeO & TiO₂ based on models fit to spectral reflectance data - and calibrated with lunar samples (1994).

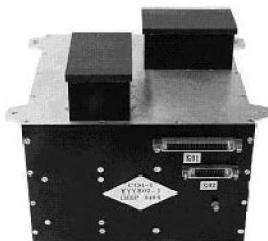
Lunar Prospector: Made global observation of major elemental abundances (Th, K, U, Fe, O, Si, Al, Ca, Mg, Ti) with a resolution of ~150km using a Gamma-Ray spectrometer (bismuth germanate scintillator) (1998).



Present Missions



Kaguya (SELENE): Will globally map (~90%) the lunar surface elemental composition using a CCD based instrument. The footprint resolution is 20km @100km and the energy resolution is <180eV @ Fe55 & -50°C. Detector area is 100cm² and 0.7 to 10keV (2007).

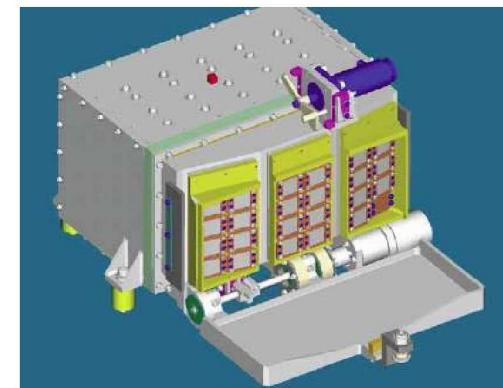


Chandrayaan-1: During this 2-year mission, CIXS (swept charge device) will map the lunar surface elemental composition (0.5-10keV range), and 20x20km FoV @ 100km. Effective area is 25cm². Expect to get Mg, Al, and Si during solar quiet and Ca, Ti, and Fe during flares (will launch 2008).



<http://www.selene.jaxa.jp/en/>

Chang'E-1: Globally map the lunar surface major elements. Energy resolution is 3.3% @ Fe55 200km orbit (2007).

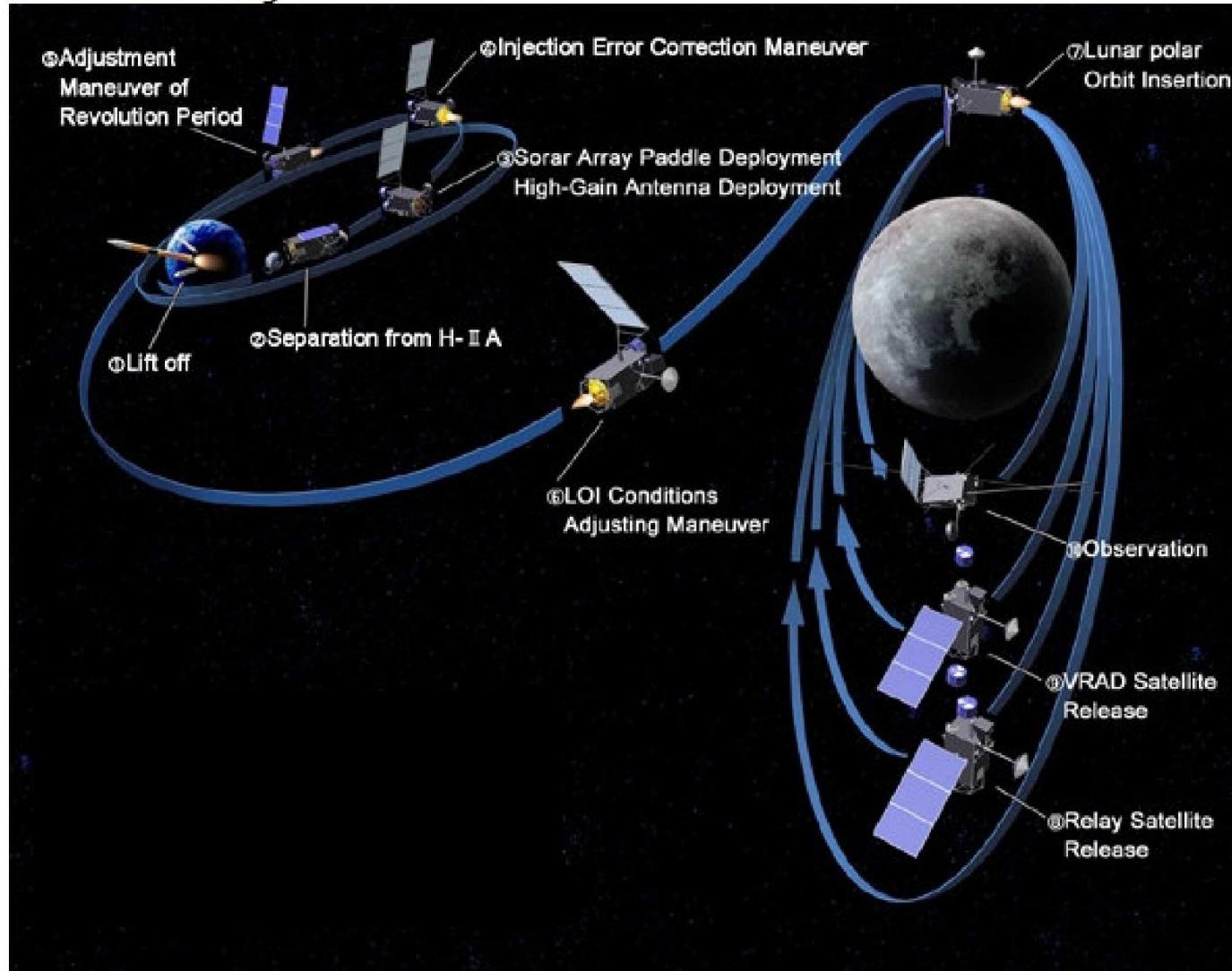




Orbit Configuration (KAGUYA)



Mission Profile Figure





Lunar Surface Science



A lunar orbiting X-Ray fluorescent spectrometer with improved sensitivity and thus, the capability for higher resolution (of a few km) would allow for unique science and a more detailed assessment of global resources.

- **Crater Probing**

- The number of craters with diameter $> d$ (meters) in a 10^6 km^2 area is given by $5 \times 10^{10} d^{-2}$ (Cox 2000, Wilhelms *et al* 1978, Cross 1966).

- The number of craters in a 10^6 km^2 area greater than 5km in diameter is 16x the number of craters larger than 20km in diameter.

- **Crater Depth/Diameter Relationship**

- Smaller craters are generally shallower - Determine Characteristics
 - Probe deeper/larger craters in detail (e.g. central crater peak, rim, walls, secondary impacts - time evolution of the lunar crust)

- **Defining Potential Landing Sites**

- The XRS will be able to clearly identify ilmenite (FeTiO_3), anorthite ($\text{CaO}\cdot\text{Al}_2\text{O}_3\cdot 2\text{SiO}_2$), pyroxene ($[\text{Fe},\text{Mg},\text{Ca}]\cdot\text{SiO}_2$), and olivine ($2[\text{Fe},\text{Mg}]\cdot\text{SiO}_2$) through their abundance ratios. Both ilmenite and anorthite are potential sources for oxygen extraction.



Problem



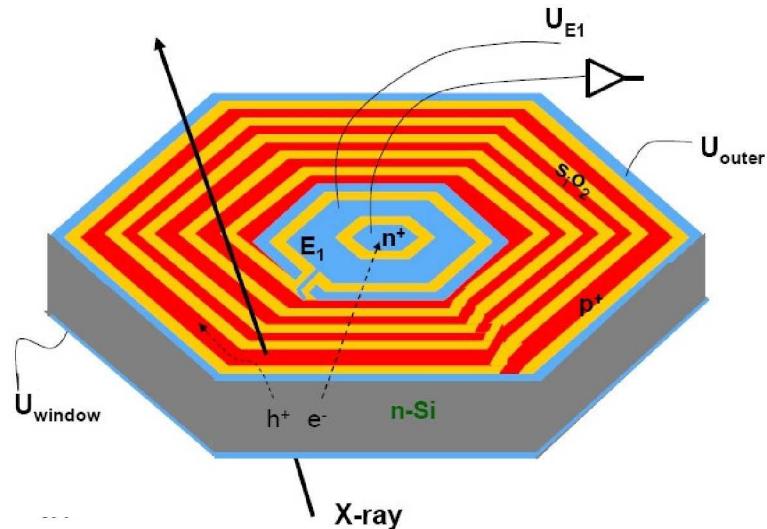
- Currently, all X-Ray fluorescent spectrometers use a CCD or CCD-type detector.
 - The problem is that CCDs are typically very power hungry. This means that the instrument size, and hence sensitivity, is limited.
 - What is needed is a detector with equivalent energy resolution to a CCD, but much lower power requirements.
 - We want a detector that has a higher spatial resolution. This dictates a larger area detector that operates with little power. The device must have good spectral resolution (low noise devices) and modest cooling requirements.
-



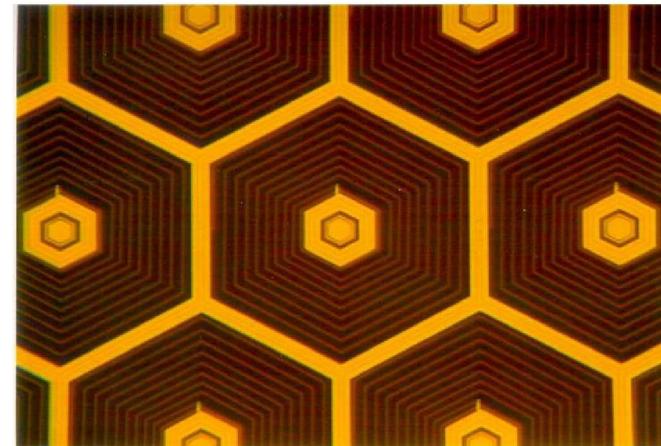
Solution



- One type of detector can satisfy all the desired capabilities .. An array of silicon drift detectors with custom readout electronics.
 - MSFC is working with Brookhaven National Laboratory to develop this type of instrument
- Single silicon wafers contain many individual detector elements (pixels)
- Each detector pixel has its own readout electronics channel - needs custom large scale integrated circuits
 - Individual pixel electronics gives very high rate capability
 - Low capacitance means good energy resolution
 - No clocking of charge packets so very radiation resistant
- Chen et al., NSSC Record, IEEE 2007



Single pixel silicon drift detector schematic.



Drift detector array (with hexagonal pixels)

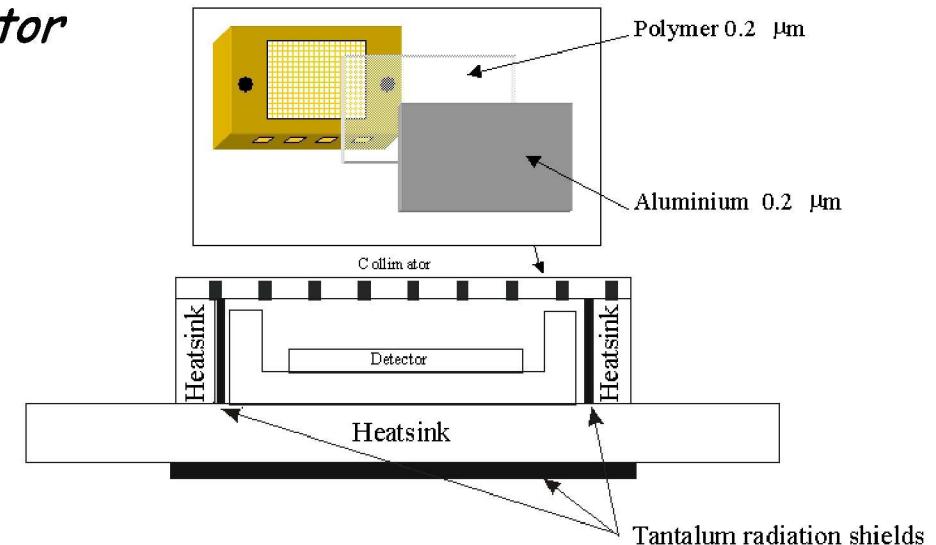
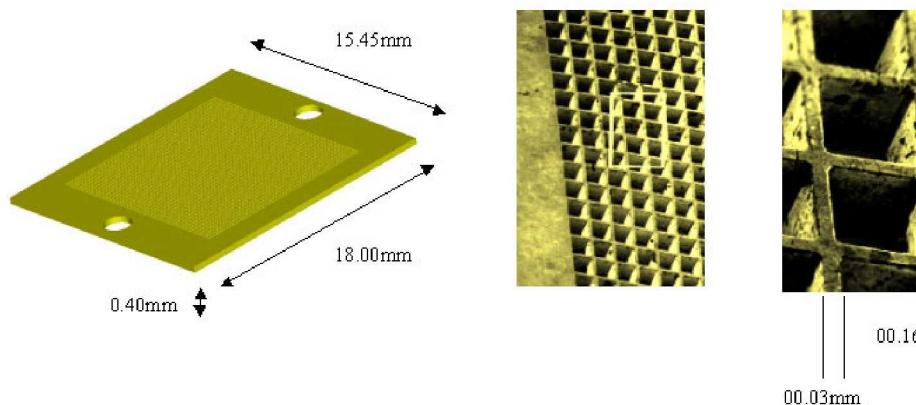


Possible Flight Configurations

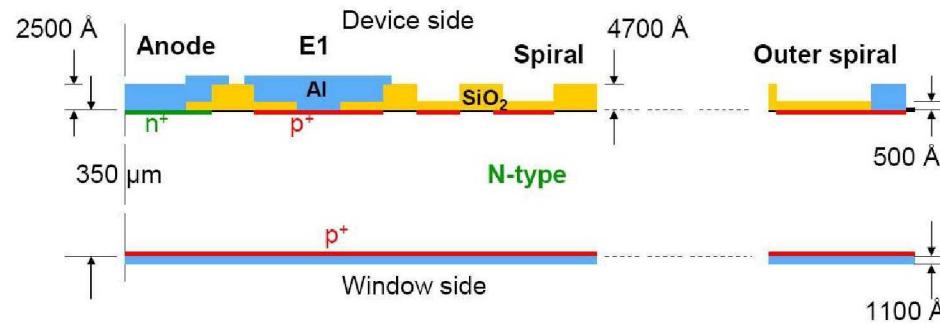


Lunar Spectrometer

- Large area, simply collimated detector



Detector Cross-Section

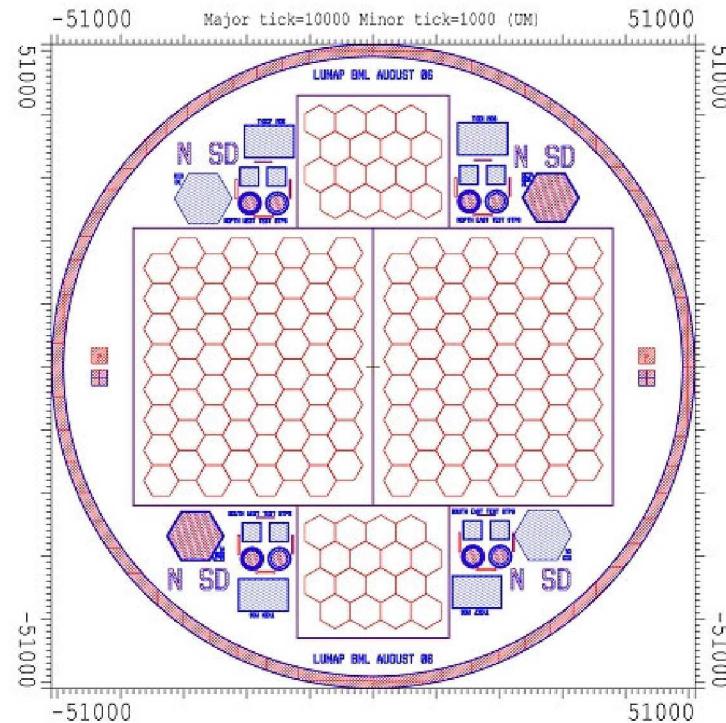




Instrument Configuration



| | |
|----------------------------------|--------------------------------------|
| Total Detector Area | 500cm ² |
| Effective Lunar Footprint @ 50km | <5km |
| Elements of Interest | Mg, Al, Si, P, Na, Fe, K, Ca, Ti, Cr |
| Energy Resolution | <200eV FWHM |
| Single Pixel Size | 20mm ² |
| Single Array Size (unit size) | 64 detectors (4 ASICS) |



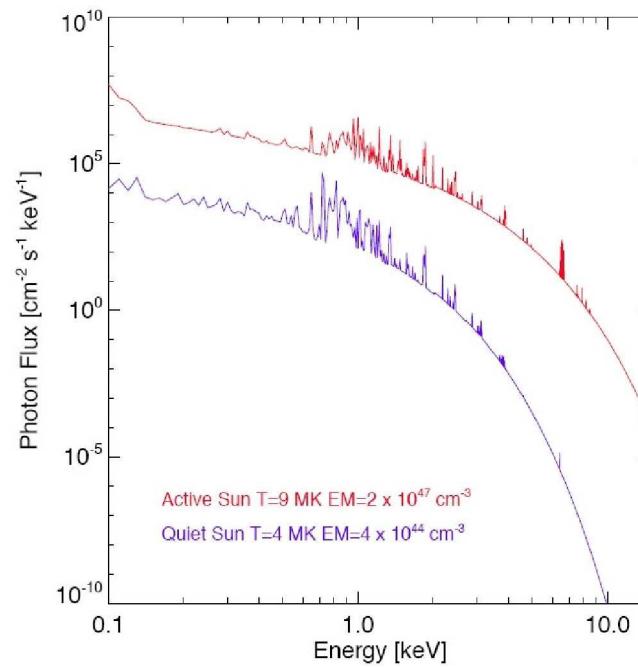
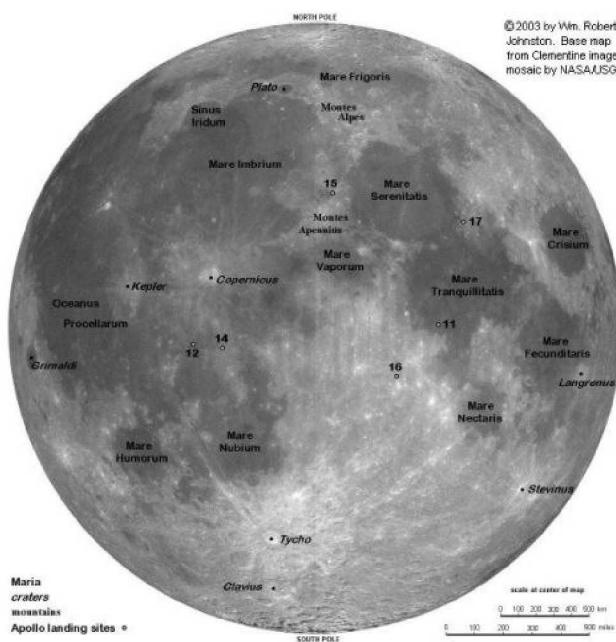
- Single 4" Wafer Layout



Expected Sensitivity



- KAGUYA's XRS-A, predicted count rates for major elements are a few hundred counts in 8 secs for a quiescent Sun*. With a detector area of 100cm² (and 100km altitude), our instrument (5x larger and 2x closer to the lunar surface) will see a 20x increase in the expected counts for the same lunar footprint.
- A simulation was performed to estimate the sensitivity if the instrument with regards to the lunar surface.
- Simulation assumed a 50km orbit and solar max spectrum. Regolith abundances were based on Feldspathic Highlands Terrain.



* Okada et al., 2002, Adv. Space Res., 30-8, p. 1909.



Expected Sensitivity



Table 2. Comparison of the composition (mass %) of the crust of the Earth to two lunar terrains, Feldspathic Highlands Terrain and Procellarum Terrain, and to lunar mare basalts.

| Z | Earth | Moon | | | | | |
|-----------------------------------|-------|------|------|--------------|------|------|--|
| | | FHT | PKT | Mare Basalts | | | |
| note | 1 | 2 | 3 | 4 | 5 | 6 | |
| 8 O | 45.7 | 45.1 | 44.3 | 42.1 | 41.9 | 40.9 | |
| 11 Na | 2.7 | 0.26 | 0.60 | 0.17 | 0.30 | 0.30 | |
| 12 Mg | 2.3 | 3.3 | 6.2 | 5.7 | 5.4 | 4.9 | |
| 13 Al | 8.2 | 14.9 | 8.8 | 6.0 | 5.7 | 5.0 | |
| 14 Si | 28.3 | 20.9 | 22.6 | 21.9 | 21.4 | 18.6 | |
| 15 P | 0.08 | 0.01 | 0.24 | 0.01 | 0.03 | 0.04 | |
| 19 K | 1.84 | 0.02 | 0.56 | 0.02 | 0.11 | 0.07 | |
| 20 Ca | 4.0 | 11.6 | 7.2 | 7.8 | 7.5 | 7.8 | |
| 22 Ti | 0.42 | 0.13 | 1.0 | 0.58 | 1.7 | 6.7 | |
| 24 Cr | 0.01 | 0.07 | 0.12 | 0.32 | 0.29 | 0.27 | |
| 25 Mn | 0.09 | 0.05 | 0.10 | 0.20 | 0.21 | 0.20 | |
| 26 Fe | 5.0 | 3.4 | 8.0 | 15.2 | 15.3 | 14.7 | |
| 90 Th, ppm | 6. | 0.4 | 16. | 0.2 | 1. | 1. | |
| oxide | | | | | | | |
| 14 SiO ₂ | 60.5 | 44.7 | 48.3 | 46.8 | 45.8 | 39.8 | |
| 22 TiO ₂ | 0.70 | 0.22 | 1.68 | 0.98 | 2.9 | 11.1 | |
| 13 Al ₂ O ₃ | 15.5 | 28.2 | 16.8 | 11.4 | 10.7 | 9.4 | |
| 24 Cr ₂ O ₃ | 0.02 | 0.10 | 0.18 | 0.47 | 0.43 | 0.40 | |
| 26 FeO | 6.4 | 4.4 | 10.3 | 19.5 | 19.7 | 18.9 | |
| 25 MnO | 0.12 | 0.06 | 0.13 | 0.26 | 0.27 | 0.26 | |
| 12 MgO | 3.8 | 5.4 | 10.2 | 9.4 | 9.0 | 8.1 | |
| 20 CaO | 5.6 | 16.3 | 10.1 | 10.9 | 10.6 | 10.9 | |
| 11 Na ₂ O | 3.6 | 0.35 | 0.81 | 0.22 | 0.41 | 0.40 | |
| 19 K ₂ O | 2.2 | 0.03 | 0.68 | 0.02 | 0.13 | 0.09 | |
| 15 P ₂ O ₅ | 0.15 | 0.03 | 0.55 | 0.02 | 0.07 | 0.10 | |
| Σ | 98.6 | 99.9 | 99.8 | 100.0 | 99.9 | 99.4 | |

Notes: (1) Mean of four estimates of the "present bulk continental crust" (Lodders and Fegley, 1998). (2) Feldspathic Highlands Terrain: mean feldspathic upper crust estimate of Korotev et al. (2003), based on feldspathic lunar meteorites. (3) Procellarum KREEP Terrain: mean Apollo 14 impact-melt breccia (Korotev, 2000). (4–6) Mean very-low-Ti, low-Ti, and high-Ti mare basalt (Korotev, unpubl. data base).

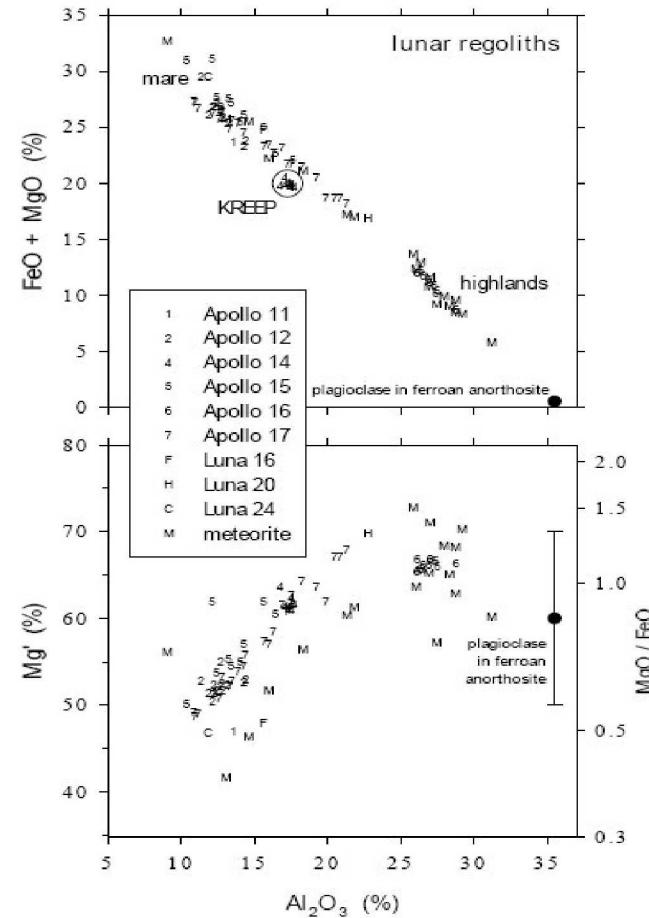


Figure 1. A strong anticorrelation in lunar samples between Al_2O_3 (and CaO) and $\text{FeO} + \text{MgO}$ is shown (top plot). However, a weak correlation between MgO/FeO and Al_2O_3 seems to exist (bottom plot).



Expected Sensitivity



The XRS should be able to clearly identify the four major lunar minerals; ilmenite ($(\text{Fe}, \text{Mg}, \text{Mn}, \text{Ti})\text{O}_3$), anorthite ($\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$), pyroxene ($[\text{Fe}, \text{Mg}, \text{Ca}] \cdot \text{SiO}_2$), and olivine ($2[\text{Fe}, \text{Mg}] \cdot \text{SiO}_2$), through their abundance ratios.

Counts/Yr (resolution element)

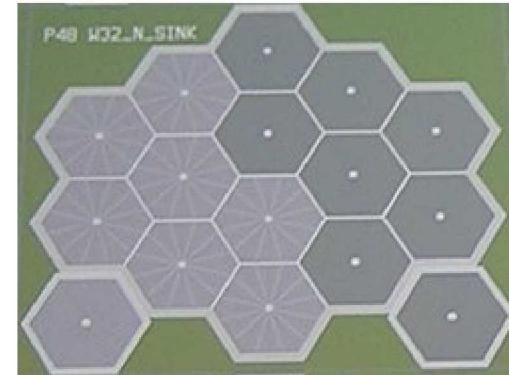
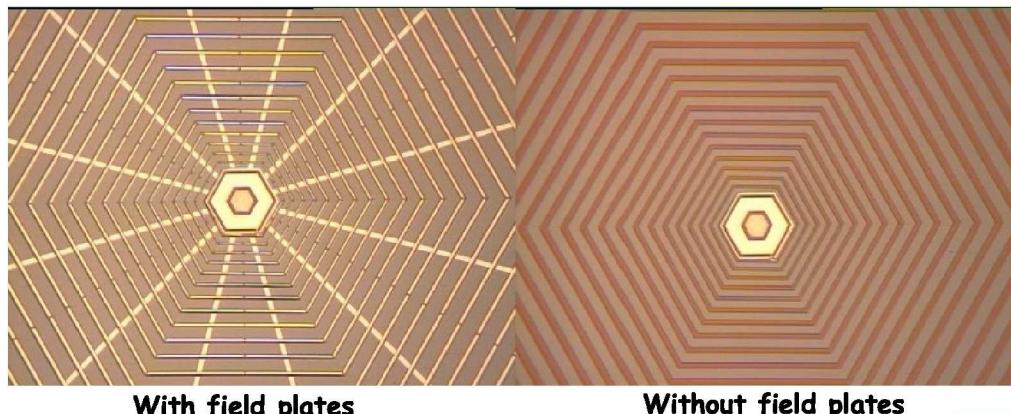
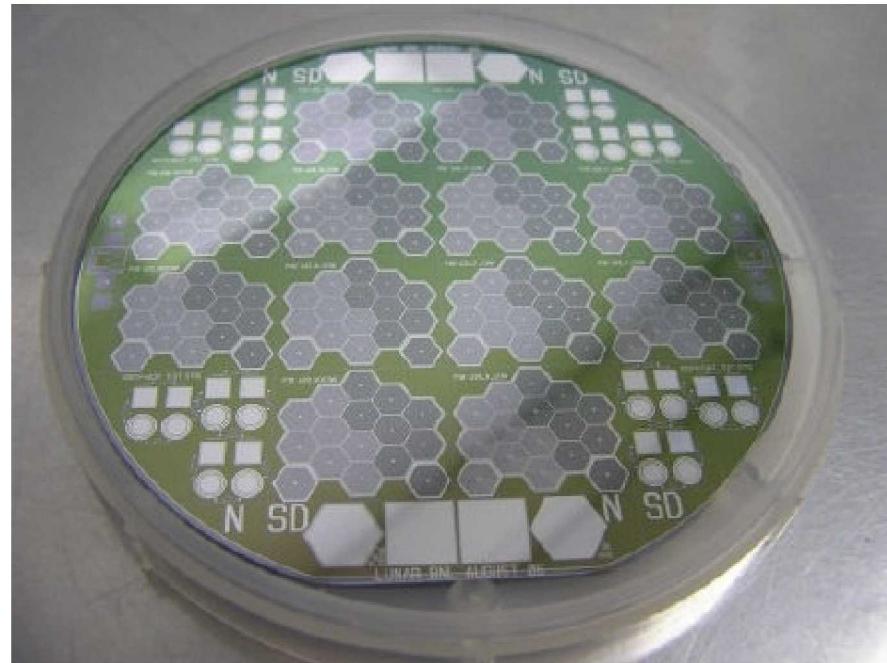
| FOV (Deg) | Resolution (Km) | Coverage (equator) | Time/Yr (Sec) | Line | O (0.45) | Na (0.003) | Mg (0.03) | Al (0.15) | Si (0.21) | Ca (0.12) | Ti (0.001) | Fe (0.034) |
|-----------|-----------------|--------------------|---------------|------|----------|-------------|-----------|-----------|-----------|-----------|------------|------------|
| 10 | 8.7 | 100% | 21.3 | K | 4139.6 | 154.8 | 764.4 | 1733.4 | 2157.0 | 216.7 | 0.00 | 1.89 |
| | | | | L | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 85.5 | 3.11 | 311.16 |
| 5 | 4.4 | 100% | 5.4 | K | 262.37 | 9.81 | 48.45 | 109.87 | 136.71 | 13.74 | 0.00 | 0.12 |
| | | | | L | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 5.42 | 0.20 | 19.72 |
| 2.5 | 2.2 | 80% | 1.3 | K | 15.79 | 0.59 | 2.92 | 6.61 | 8.23 | 0.83 | 0.00 | 0.01 |
| | | | | L | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.33 | 0.01 | 1.19 |



Project Status



- 2 sets of identical detector types have been fabricated at BNL and KETEK GmbH (Munich, Germany).
 - 24 detector patterns (12 with Al field plates and 12 without) - varying spiral pitch and width.
 - Each array has 14 active pixel elements
- A first-iteration low-noise ASIC has been developed* and tested, second iteration is underway.
- Detector/ASIC arrays have been tested in the lab with an Fe55 x-ray source, in the BNL Instrumentation Division, and in the BNL NSLS beamline U3c (50-1000eV).



* De Geronimo et al., 2007, NSSC IEEE Proc.



Beamline Tests (Feb. 2008)



Experiments at NSLS: Beamline U3C

Source Type: Bending Magnet

Energy Range: 50-1000eV

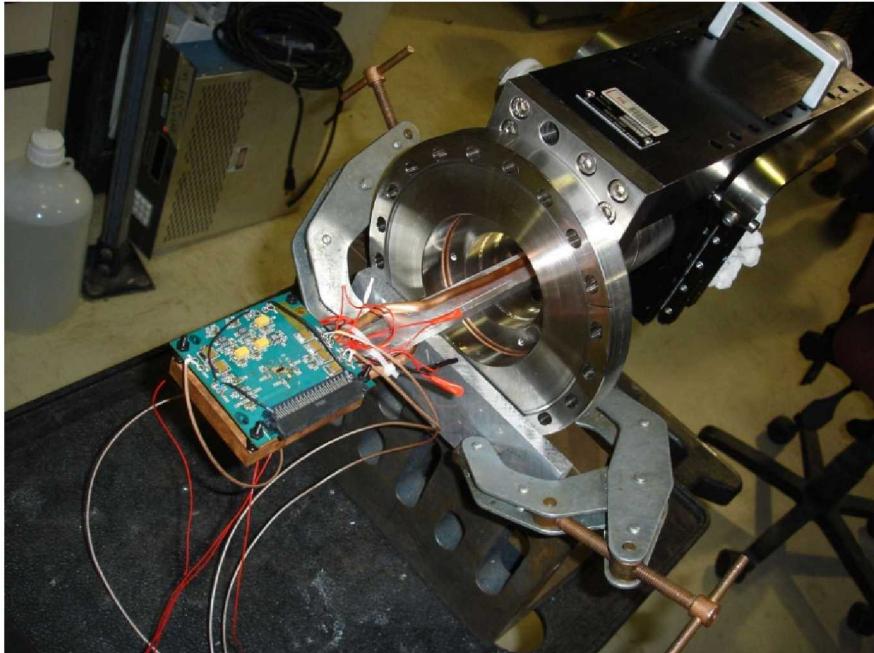
Resolution: 1.5eV @450eV

Flux: 7×10^8 ph/s @400eV

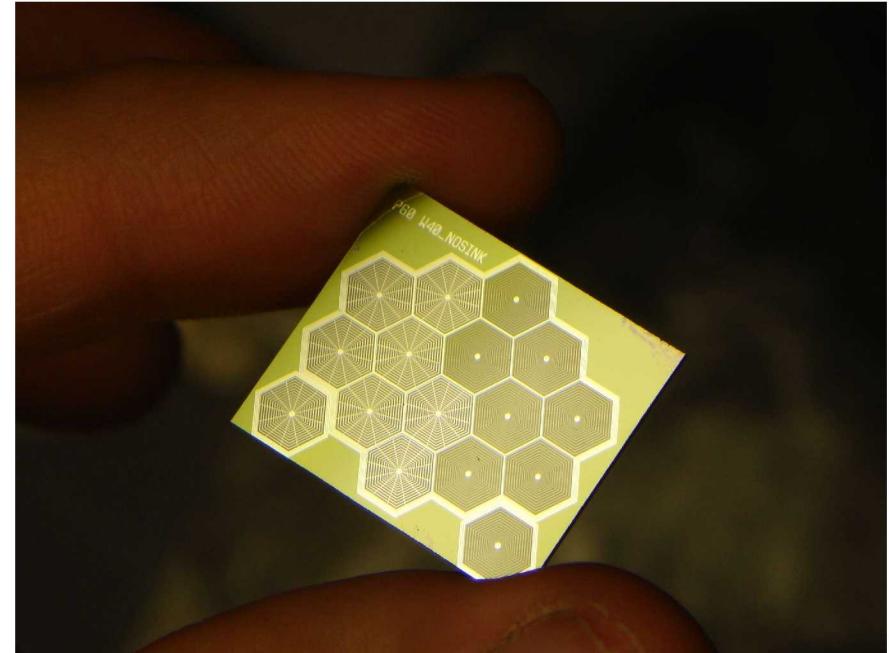
<http://www.nsls.bnl.gov/beamlines/beamline.asp?blid=U3C>



Beamline Tests



a)



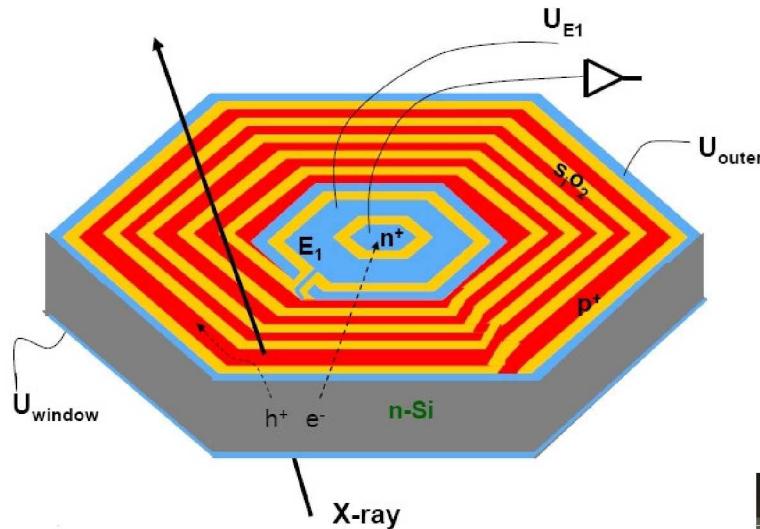
b)

Experimental setup: a) detail of cooling system and stages with detector mounted. The sensor is not visible. b) A sensor: chip with 14 SDD and 2 test structures.

The detectors were cooled to -27°C , and a $25\mu\text{m}$ pinhole was used to define the beam.

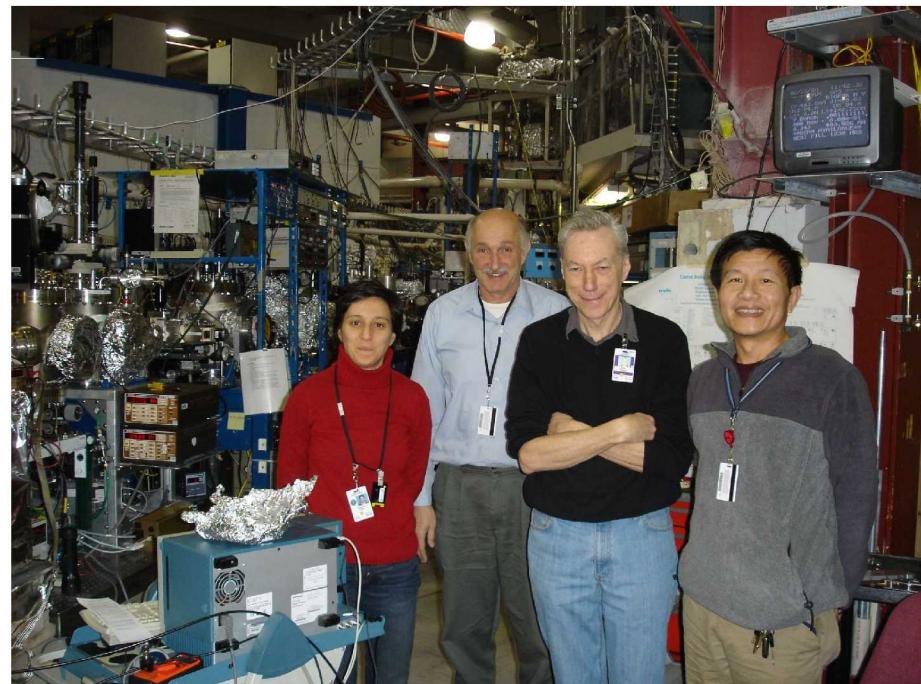


Beamline Tests - Detector Biasing



$$\begin{aligned} U_{\text{window}} &= -60 \text{ V} \\ U_{E1} &= -10 \text{ V} \\ U_{\text{outer}} &= -120 \text{ V} \end{aligned}$$

Happy NSLS users!

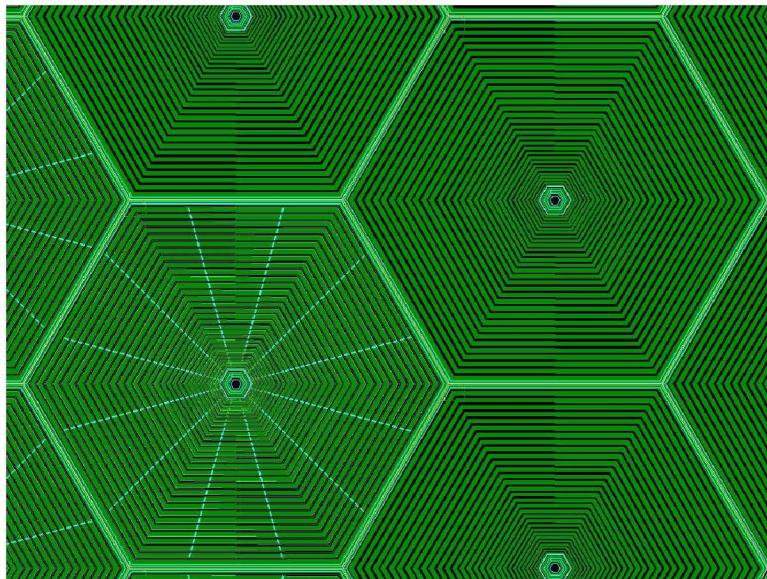




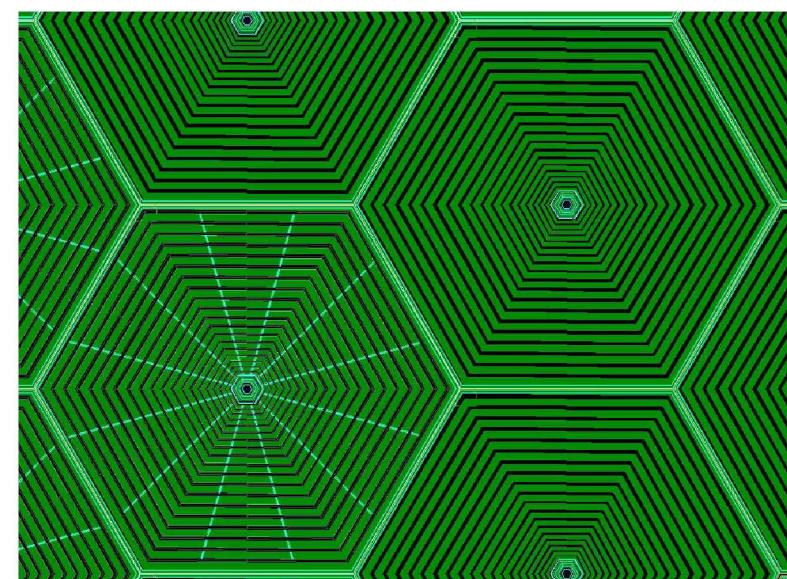
Detectors Tested



- Two detectors were tested in the beamline: KETEK detector P30W20_N_sink and BNL detector P48W30_N_sink.*



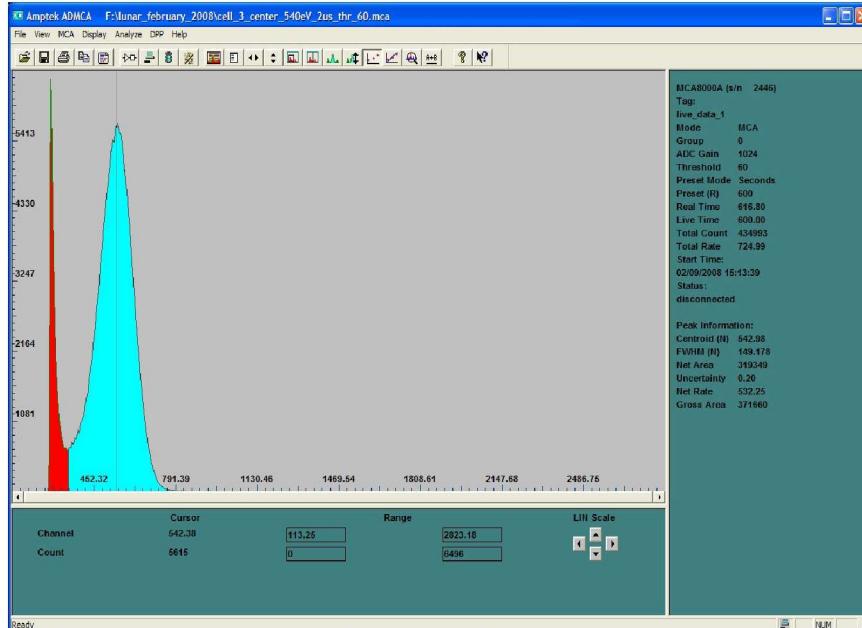
P30W20_N_sink



P48W32_N_sink



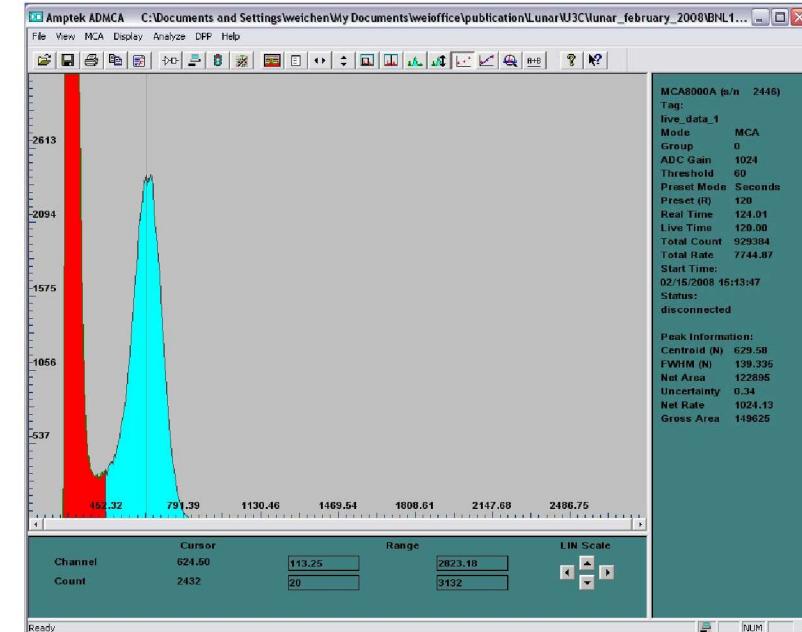
Beamline Tests



a)

Spectra was taken of the of 540eV x-rays incident on a single pixel in each of the pixel arrays; (a) KETEK detector P30W20_N_sink and (b) BNL detector P48W30_N_sink.

b)



The FWHM resolution was measured (using an MCA) to be 149eV for the KETEK detector and 140eV for the BNL detector. Results were bias dependent.

Overall, the smaller spiral pitch pixels, with Al field plates, proved to be the preferred design.



FUTURE WORK



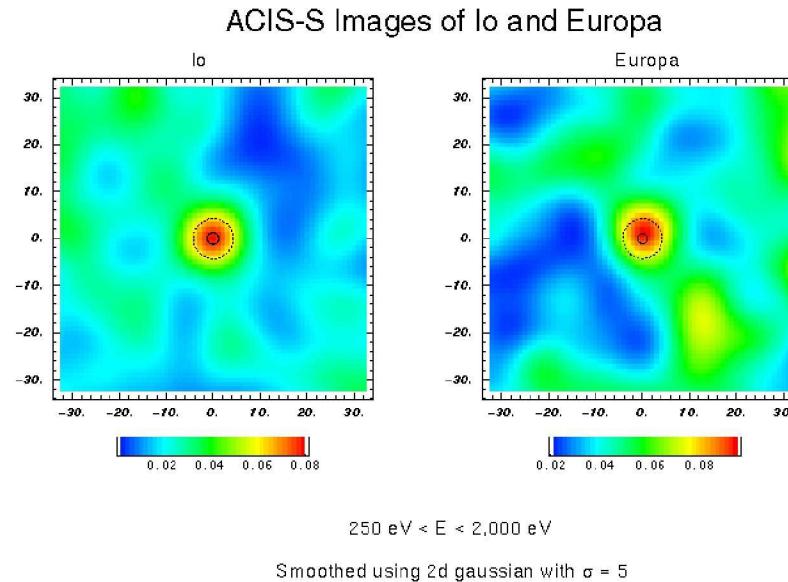
- *Next NSLS Beamline Run*
 - *Modify the existing cooling system*
 - *Redesign the bonding pad and its position on the detector to reduce capacitance*
 - *Re-measure the efficiency/response of the detectors at different energies*
 - *Re-measure cross scans across the pixels (which was non-uniform in some cases)*
 - *Measure different arrays designs*
 - *Redesign/fabricate second iteration ASIC to accommodate 16 channels for new detector configuration. Fix any other existing issues.*
 - *Fabricate/test new BNL & KETEK detectors (using new array structure and lower resistivity material)*
 - *Determine final array assembly structure and collimator design*
 - *Complete thermal models for cooling detectors*
-



Jupiter Icy Moons Surface Analysis



- For Jupiter's icy moons (Europa, Ganymede and Callisto) the surface fluorescence is stimulated by charged particle irradiation from Jupiter's radiation belts.



For sensitive measurements, once again need a spectrometer in orbit around the moons. Need low-power, high-spectral-resolution detector as for the lunar application, but also, because you are in radiation belts, need very high rate capability and very high radiation resistance. This completely rules out CCD detector.

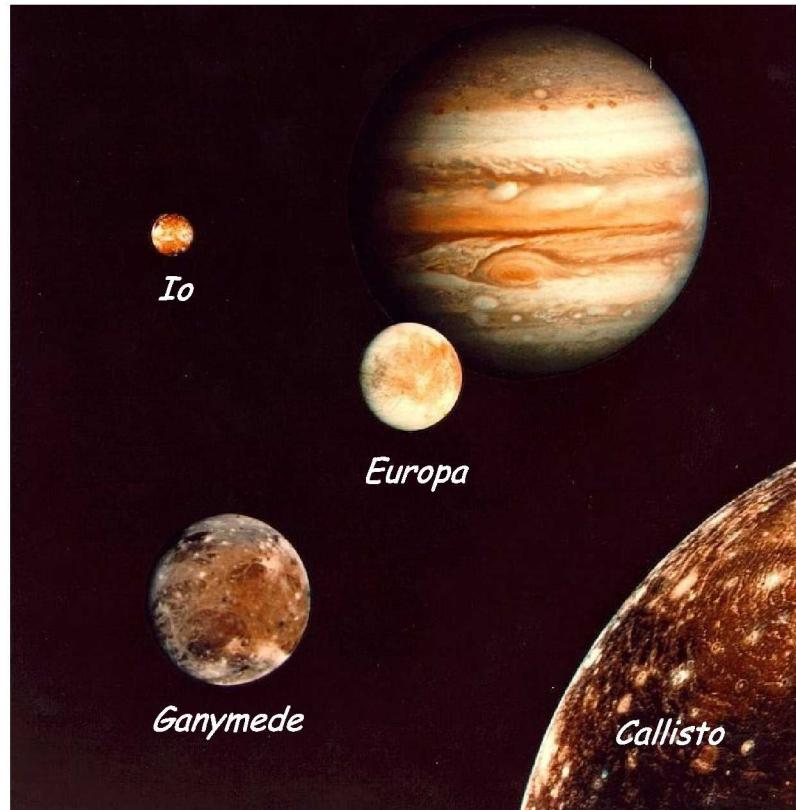
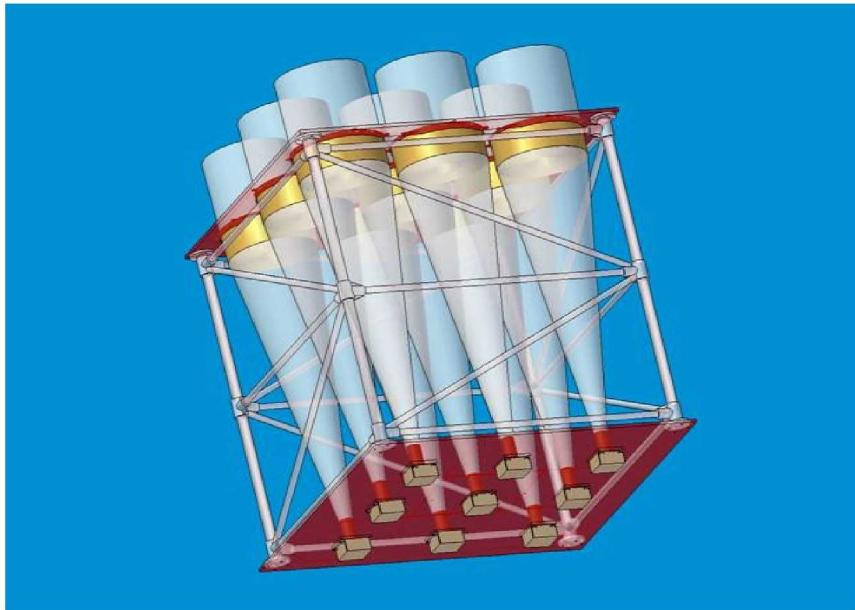


Jupiter Icy Moons Surface Analysis



- Jupiter Icy Moons

- Use focusing x-ray optics to reduce overall data rate and increase signal to noise ration...need array of small detectors



NASA / <http://www.windows.ucar.edu>

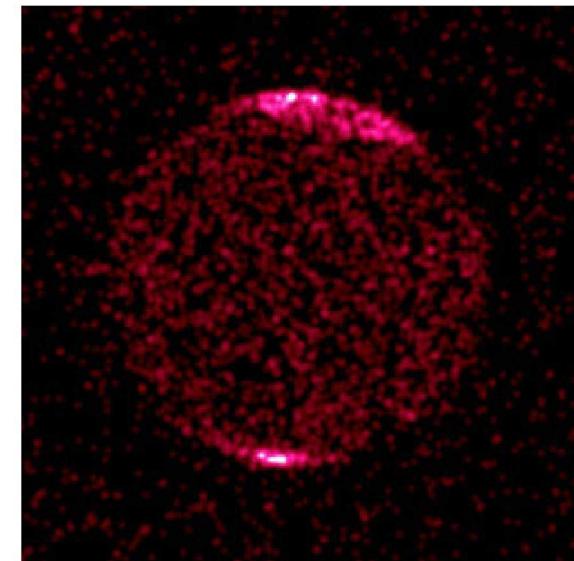


Jupiter Icy Moons Surface Analysis



X-Ray fluorescence mapping of the Jovian system will help to answer some of these questions regarding the origin and evolution of a potentially habitable planetary system.

- What planetary processes are responsible for generating and sustaining habitable worlds?
- Where are the habitable zones in the solar system?
- How has the suspected ocean varied throughout Europa's history?
- What is keeping the ocean from freezing?
- How do the processes that shape the contemporary character of planetary bodies operate and interact?
- What is the chemical composition of Europa's suspected ocean?



<http://chandra.harvard.edu/>



Possible Applications/Missions



Currently, there is not a specific mission to accommodate this instrument. However, the Lunar Exploration Analysis Group themes/goals includes:

- *Theme 1:*
 - Pursue scientific activities to address fundamental questions about the solar system, the universe, and our place in them.
- *Theme 2:*
 - Use the Moon to prepare for future missions to Mars and other destinations.
- *Theme 3:*
 - Extend sustained human presence to the Moon to enable eventual settlement.

- *Goal 1A: Understand the formation, evolution and current state of the Moon.*
- *Goal 1B: Use the Moon as a "witness plate" for solar system evolution.*
- *Goal 3D: Facilitate development of self-sustaining economic activity.*

**There is a high probability for a future mission with the need for an x-ray fluorescent spectrometer.*



Other Possible Applications



Applications for this instrument other than for the Moon and Jupiter includes:

- *Comet Rendezvous Missions.....specific AO*
- *Earth/Sun Interaction Missions*
- *Asteroids and Other Airless Bodies Missions*

Gaspra



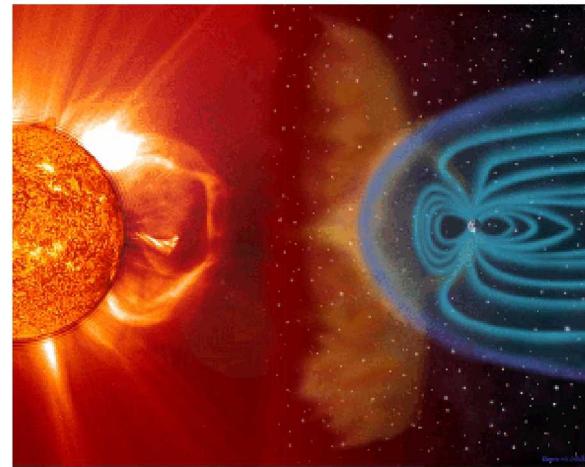
NASA/JPL

Deep Impact - Tempel 1



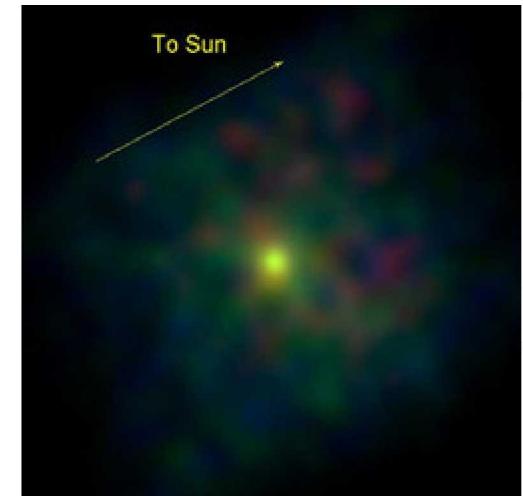
www.nasa.gov/mission_pages/deepimpact

Sun-Earth



www.star.uclan.ac.uk/solar/group

Tempel 1



NASA/CXC/C. Lisse & S. Wolk

<http://chandra.harvard.edu>